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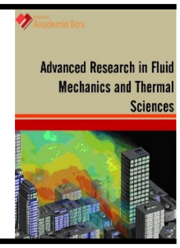

Photovoltaic Thermal /Solar (PVT) Collector (PVT) System Based on Fluid Absorber Design: A Review

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A.L. Abdullah[1,3,*], S. Misha[1,2], N. Tamaldin[1,2], M.A.M. Rosli[1,2], F.A. Sachit[1,3]

[1] Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal,Melaka, Malaysia
[2] Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3] Ministry of Electricity, Baghdad, Republic of Iraq

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ABSTRACT

Photovoltaic thermal (PVT) is a hybrid system, which incorporates both thermal and electrical energy generations. PVT can be used as a cooling system for the PV system in order to enhance the electrical energy efficiency and at the same time, produce thermal energy, which can be used in other applications. There are various types of PVT collectors including water or air, based on the fluid used in the PVT system. This paper aims to review the advancement and progress in the field of PVT collector based on water fluid. The review investigated various research articles by analysing their proposed designs of PVT collector and absorber. The shortcomings and drawbacks of the available PVT collector are presented in order to show the research gap in the field of PVT collector-based water. Different PVT collectors and absorbers configurations are presented and discussed. The study concludes that water-based PVT are widely used and produce improved efficiency as compared to the air-based PVT.

Keywords:
Photovoltaic–thermal collector PVT, absorber, electrical efficiency, thermal efficiency

1. Introduction

Currently, electrical energy is the backbone of our modern life as it is extremely needed to operate any equipment, device or system. Technological advancement and an increase in the population contribute to the rising energy demand. The increasing demand for electrical energy requires a large increase in energy generations [1]. Most of the available energy resources are traditional resources that are expensive in terms of installation and use. Also, these resources are linked to adverse environmental consequences such as global warming, greenhouse emission, and climate change. Thus, efforts are now being directed to finding renewable energy resources, such as solar energy, that can provide energy naturally and mitigate the impacts to the environments caused by traditional resources or fossil fuel based resources [2,3]. The utilisation of solar energy has become a focal point in many research and industries in multiple countries, so as to provide clean energy resources that are produced naturally and have less impact on the environments. In order to

* *Corresponding author.*
E-mail address: amiraaljboury@gmail.com (Amira Lateef Abdullah)

generate energy from the sun, various converting techniques, such as converting solar energy into electricity or heat and exploiting the biochemical reaction, are applied [4]. The use of solar energy in solar thermal collector and PV equipment markets is not new and is steadily improving, especially in terms of energy saving and minimising the environmental effects.

The solar thermal design is considered as one of the best cost-efficient renewable resource systems and has a big global growth potential. They account for more than 90% of the globe-utilised solar capability which are used in powering, for instance, hot water usage and air heating, solar-assistance cooler, and industrial process heating. PV/thermal (PV/T) systems enable both the tasks of solar collection in one system and the generation of electrical and thermal energy. This integration of PV and thermal collectors does not only enhance PV effectiveness, it also produces more energy in a certain area than a singular PV cell or solar collectors alone. Other features of PV/T systems include a lower installing cost and symmetric façade appearance.

Recently, there is a growing concern about the environmental effects of energy usage. This concern and the increasing cost involved in generating energy encourage researchers to look into alternative and renewable energy sources, especially solar energy, which can reduce the dependency on non-renewable energy resources or fossil fuel-based resource [3].

Solar energy can generally be classified into two areas of study; (i) solar thermal, in which the radiations received are transformed into heat, and (ii) Photovoltaics (PV), in which solar energy is transformed into electrical energy. The solar thermal design is commonly used for the water heater, space heating, and energy production. Traditionally, solar thermal and photovoltaic systems often existed as separate systems in many applications. In the 1970s, research started to focus on combining solar thermal design and photovoltaic systems into a one-design system, known as Photovoltaic/Thermal (PVT) solar collectors. The combination of these systems offers two benefits: (i) an increase of photovoltaic cells effectiveness, in which they can be frequently cooled through the solar thermal system, and (ii) a reduction in space utilisation. It is known that photovoltaic cells experience an efficiency drop in response to any temperature rise and thus can be minimised with a solar thermal system utilising PVT design [5].

One of the factors influencing the stability of PV cells is their corresponding lower efficiency. To date, the commercial PV cell effectiveness, as assumed by manufacturing companies, is in the range of 6% to 16%. This assumed effectiveness is under the normal thermal rate of 25^{o}C. However, in the real world, especially for cities with a hot climate, the thermal rate can reach up to 35^{o}C. The increment of the PV thermal rate consequently reduces cell effectiveness. A research conducted by Michael *et al*., [5], in order analyze the impacts of thermal rate on the behavior of silicon solar cell type, the study gather the measurement of current and voltage of the cell at different temperature with a constant radiation at 1000W/m^2. The study found that the reversing saturated current was the most influenced parameters in response to the temperature rise. Hence, to minimise the drop in PV cell efficiency, an instant cooler design utilising air or fluid as the heat transferring method is suggested. The heating produced by the cooling system may be gathered and saved as heating energy. This sophisticated system is recognised as the PV/T system. A PV/T system is an integration of PV cells and thermal model or systems that are able to generate electricity as well as heat energy simultaneously.

In the last four decades, there are a number of studies and project implementation on PV/T systems [5]. PV/T systems may be categorized into water-based PVT and air-based PV/T systems. The PV/T/water design is more effective because of its better thermo-physical features compared to air designs [6]. In contrast, PV/T/air designs are favoured because of their lower constructing and operating cost. Several models of PV/T collectors have been implemented and investigated covering different absorber designs. A thinner thermal absorber with PV/T model was verified by Xu *et al*., [7], where the introduced absorber with PV/T is compared to the traditional PV model. The study findings indicated that a 5% efficiency improvement was obtained when using thin thermal absorber based PV/T system than the conventional PV system, as well as a 3.5% increase in the overall energy production. In addition, PV/T behaviour was investigated with different absorber designs in [8]. Seven absorber designs were investigated and simulated to find the best design that can enhance the system's efficiency. The spiral flow absorber design was found to be the best design with regards to the thermal and PV effectiveness. Many other studies focusing on the behavior of the PV/T system were conducted in both simulation and experimental testing [9-11].

Various combined photovoltaic thermal collector designs were studied by Kim and Jun [12]. The study focused on the yield of these designs by implementing nine different models. The result indicated that the channel-under-transparency-PV system obtained optimum effectiveness when compared to other designs. Photovoltaic thermal (PV/T) collectors can be categorised into two types, namely liquid PV/T collector and air-cooled PV/T collector. Liquid PV/T collector uses terminals for directing fluid flow through pipes from different materials. There are two systems of liquid PV/T collector; (i) glass-covered collector (glazed) and (ii) uncovered collector (unglazed) [13]. Another collector design is the air-cooled PV/T collector, which features a hollow or conducting metal to mount the photovoltaic cells [14]. Hybrid liquid/air PVT collectors can be developed to extract the heat from the PV cell and enhance the system efficiency [15]. Apart from that, different thermal absorber designs can be utilised depending on the application. The study discussed various designs of thermal absorber along with performance comparison between them with regards to solar and thermal efficiency. Most of the previous studies focused on using air type PVT collectors [16] or liquid (water) PVT collectors [16,17]. However, liquid PVT collectors are the most utilised collectors due to their big range of applications, while air PVT collectors are limited in usage, especially in the summer climate situation [18].

2. Photovoltaic Thermal (PV/T)

Photovoltaic thermal collector (PVT) can be categorised into two popular types; water-based PVT and air-based PVT in accordance with the fluid used in the system. Recently, numerous studies were conducted in developing PVT collector based on water or air. In this section, PVT collectors will be examined with a focus on water-based PVT collector.

A. PVT Air Collector

The performances of the photovoltaic–thermal air collectors have been studied extensively by researchers. The behaviour of single-pass and double-pass joined PV/T were analysed with steady-state conditions. The outcomes indicated that the double-pass PV/T collector had superior behaviour over the single-pass PV/T collector. At a length of 1m, a mass flow rate of 200–300 kg/h, and pack factor of 0.5, the thermal, PV, and PV/T efficiencies were 24–28%, 6–7%, and 30–35% respectively for the single-pass PV/T. The thermal, PV, and PV/T efficiencies were 32–34%, 8–9%, and 40–45% respectively for the double-pass PV/T [1,2]. To enhance thermal extraction from the PV cell as a PV/T based air by natural flowing, a thinner metal sheet was placed at the center or fins were placed to the rear wall of the air-channel. REF module contains a basic air channel placed at the back of the PV cells, whereas the TMS has a thinner metal sheet placed at the center of the air channel and the FIN model contains fins of rectangular shapes placed on the other side of the wall to the PV back surface parallel to a flowing direction. The enhanced model showed good workability than the normal type. For the glazed enhanced model, the TMS possessed about 41°C and FIN possessed about 10°C less thermal rate than that of the REF module at a channel depth of 15cm and showed, accordingly, about 4% and 10% enhancement in output energy [3,4].

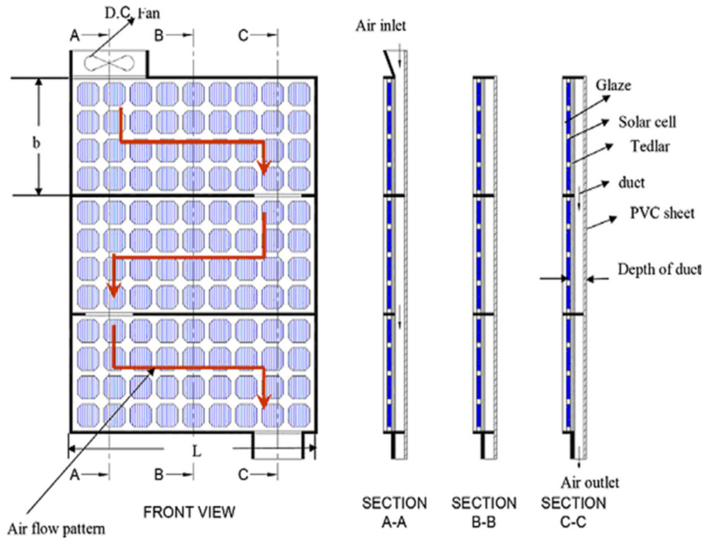

Fig. 1. PVT air collector [5]

B. PVT Water Collector

The performances of a Photovoltaic Thermal (PV/T) solar water heater were recorded from February until April 2007. It was noticed that the storage tank water thermal rate in February 2007 changed from a minimum of 29°C at 10:00 to a maximum of 59°C at 14:00; from 32°C at 10:00 to 80°C at 15:00 in March 2007; and from 34°C at 9:00 to 62°C at 16:00 in April 2007. Figure 2 presents the hourly changes in cell thermal rate and cell efficiency. It can be seen in the figure that the increase in the cell thermal rate reduced the cell effectiveness. When the cell thermal rate at 10:00 was about 34°C, the cell effectiveness was about 11.6%. When the cell thermal rate at 13:00 was about 50°C, the cell effectiveness was about 10.7% [6].

The heat, electricity and energy gains of combined photovoltaic thermal (PVT) water-based separate fixed collected thermal type for two distinguished models referred to as condition A (collector partly wrapped by the PV cell) and condition B (collector totally wrapped by the PV cell) were investigated. It was found that condition A was much preferable for hot water generation, whereas condition B was better for electrical energy generation. The outcomes showed that the yearly thermal power utilisation was 4167.3 kWh and 1023.7 kWh, and the total yearly electricity utilisation was 320.65 kWh a 1377.63 kWh for condition A and B respectively. The yearly total thermal power gains were reduced by 9.48% and the yearly total exergy gain was reduced by 39.16% from condition A to condition B [8-10].

The behaviour of facade-integrated combined PV/T models with EPV (film cell) and BPV (single silicon cell) cells for usage in the resident houses of Hong Kong were accomplished. The outcomes indicated that the yearly electrical effectiveness of the combined EPV/T and BPV/T models were 4.3% and 10.3% for a west-facing panel, and the yearly total heat effectiveness were 58.9% and 70.3% respectively. The yearly effectiveness of the water heater models were 47.6% (for EPV) and 43.2% (for BPV). The equivalent amount of days in a year if the water thermal in the storage tank gets 45°C and more were 195 and 217. The decrease of space-heating utilisation via the two types of combined

PV/T collectors wall was recorded at 53.0% and 59.2% respectively, in comparison to the normal concrete wall [11].

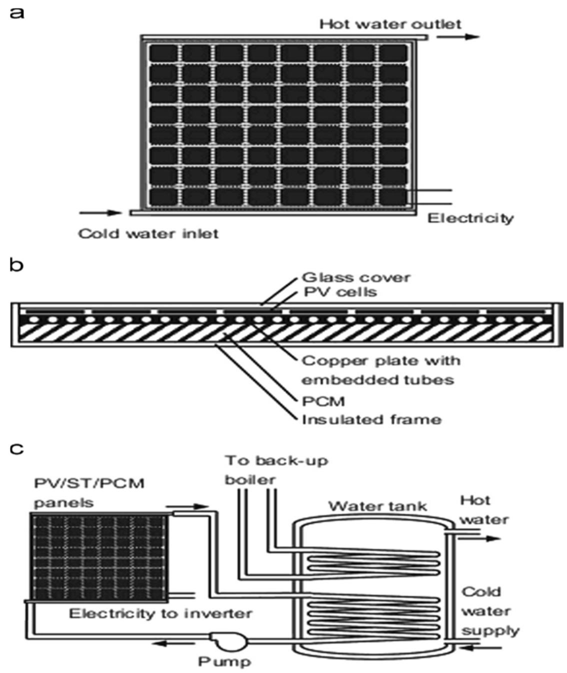

Fig. 2. Schematic model of PVT collector [7]

The thermal and PV effectiveness of two types of thermal collectors in a commercial system PV/T model were investigated in a tropical weather situation of Singapore. Type A is thermal collectors with monocrystalline Si solar panels and combined with a tube and sheet. Type B is thermal collectors with multi-crystalline Si solar panels and combined with a parallel plate. Figure 3 shows the cross-sectional areas of the flow channels for the two types of PV/T.

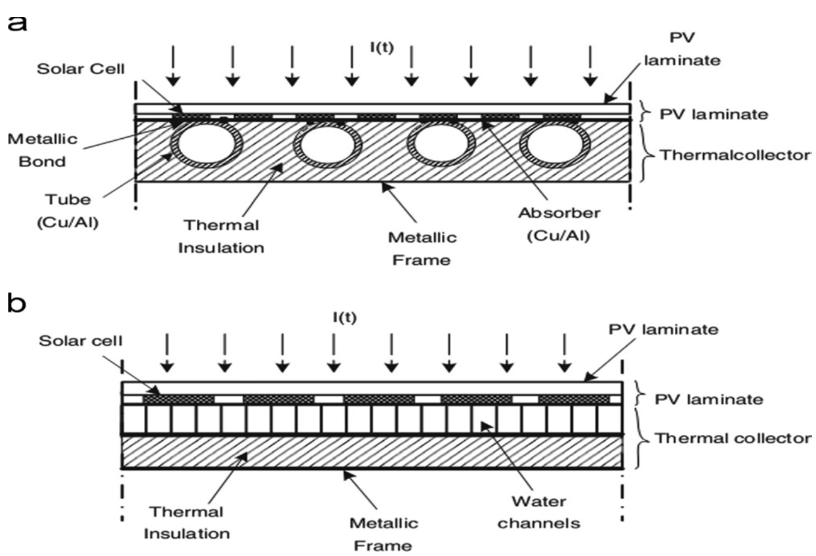

Fig. 2. Cross-sectional areas of Type A and B [12]

The electrical and thermal behaviour of the heat-pipe Photovoltaic/Thermal (HP-PV/T) models were analysed in Hong Kong, Lhasa, and Beijing; three places representing the different weather conditions in China. A part of aluminum plate was selected as the base panel. The evaporator part of the heating pipes was attached to the rear of the aluminum plate and the condenser part was attached to a water tank. It was observed that the yearly thermal power was 1665.05–1872.22 MJ/m^2, 2939.67–3328.25 MJ/m^2, and 2111.07-2352.95 MJ/m^2 when the model with an auxiliary heating system was used in Hong Kong, Lhasa, and Beijing respectively. The yearly electricity generated were 261.32–264.98 MJ/m^2, 462.14–466.1 MJ/m^2, and 322.84–328.15 MJ/m^2 in Hong Kong, Lhasa, and Beijing respectively. It can be concluded that the solar thermal production primarily relied on the existing solar radiations and the hot-water load per unit collection area (Mw/Ac). With the Mw/Ac at 64.5kg/m^2, the yearly solar thermal production of the HP-PV/T model in Hong Kong, Lhasa, and Beijing were recorded at 68.5%, 80.5%, and 64.7% respectively [13,14].

The PV/T water heater model was developed with a normal circulation and experimental tests were carried out with various water masses and various primary water thermal rates in an outside environment. Figure 4 illustrates the setup of the combined PV/T water collector. The hardware setup was implemented from 15 battens, with an overall heat-collection area of 1.76m^2. The overall PV/T design was covered in an Al-alloy framework, obtaining the total dimension of 1.33m and 1.5m. The outcomes showed that as the heated water load per unit heat-collection area was more than 80kg/m^2, the diurnal electrical effectiveness was about 10.15%, the features diurnal thermal effectiveness was more than 45%, the features diurnal overall effectiveness was more than 52%, and the features diurnal initial energy saved was about 65%, for this model with a PV panel covering factor of 0.63 and a front-glazing transmissivity of 0.83 [15].

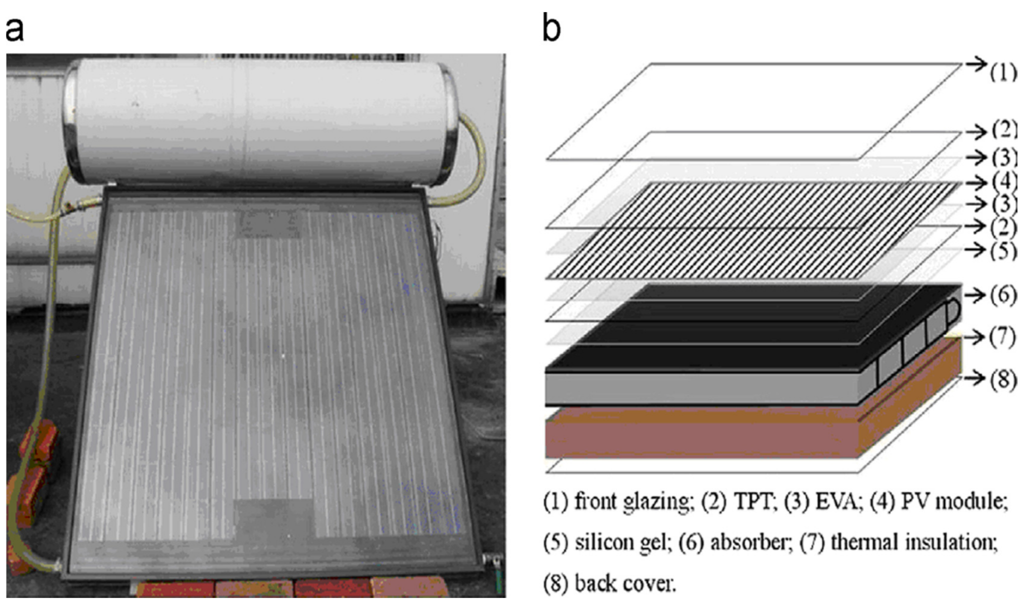

Fig. 4. The Hybrid PV water collector [16]

3. Related Studies on PV/T Based Water

Kern and Russell [17] first designed and operated combined Photovoltaic/Thermal model in accordance with ASHRAE criteria and implemented at Texas University. The study indicated that combined Photovoltaic/Thermal model generates more energy per unit area than the single PV and solar thermal model. It was also more cost-effective in comparison to traditional photovoltaic cell and solar thermal collectors.

Suzuki and Kitamura [18] constructed two types of combined Photovoltaic/Thermal model by placing three diameters of solar panels to two water class flat plate solar thermal collector. One PV/T model was an insulated value class photovoltaic/thermal model, and another was straight value class photovoltaic/thermal system. In the insulated value class PV/T model, 108 silicon solar panels were attached in three parallel settings with 36 solar panels in every parallel set. In the straight value class PV/T model, 18 small flat plate PV/T collectors were attached sequentially with every collector having 6 attached parallel solar panels. Thermocouples were utilised to measure the temperature of the photovoltaic panel and water. It was claimed that maximum energy generated by the straight mount class was 42.8 W while maximum energy generated by insulated value class was 44.8 W. Thus, it was concluded that the straight value class PV/T model was more effective in thermal collection when compared to the insulated value class.

Andrews [19] investigated the technical and economic characteristics of photovoltaic/ thermal models by conducting three experimental testings. First testing compared the photovoltaic/thermal model with a basic photovoltaic cell while the second testing compared the photovoltaic/thermal model with a solar thermal model. The third testing compared the photovoltaic/ thermal model with both the photovoltaic cell and thermal system. It was observed that for a moderate temperature implementation, a PV/T model was not a better choice as compared to the solar thermal model, whereas for a lower temperature implementation, PV/T was shown to be the better choice.

Chow *et al.*, [20] constructed a combined photovoltaic/thermal model in which the solar thermal collector with an aperture area of 1.64 m2 was integrated at the back of a photovoltaic cell of 72 W. The ending size of the solar thermal collectors was attached to two aluminium traverse heading, where input and output sides were placed at the upper transfer traverse heading. Water went through the rectangular flow channels constructed from aluminium, (as presented in Figure 5) which was integrated at the back of a PV cell and absorbed its heating with a normal circulation of water. A numerical system was designed by applying a finite-difference control volume approach and verified with experiment testing investigation. The electrical effectiveness and thermal effectiveness of photovoltaic/thermal model were recorded to be 10.7% and 48.6%.

Tiwari and Sodha [21] designed a combined integrated solar model where the thermal rates of a photovoltaic panel and collector water were obtained analytically in accordance with an energy balance system. Photovoltaic/thermal system contained of aluminum water channel via where water cooler was passing from an isolated cylindrical storage water box of 45 kg capacity. It was claimed that the total efficiency had crucially enhanced from 24% to 58% by flowing water under PV panel where is closer to experiment amount (61.3%) recorded by Huang *et al.*, [48]. The study concluded that a better mass flow rate of water was in the range of 0.005 kg/s and 0.075 kg/s.

Ji *et al.*, [22] constructed a house incorporating photovoltaic/thermal model (BIPVT) and analysed the influences of packing factor and water mass flow rate on the thermal and electrical behaviour of wall compound water-based PV/T. In BIPVT model water was flowed via 6 photovoltaic/thermal collectors with an aperture area of 1.173 m2 with water pumping. Higher and lower PV/T thermal collectors were attached in sequence, making 3 pairs in a parallel placement. It was found that as the pipe diameter increased from 0.01m to 0.02 m, pumping energy decreased accordingly. However, an oversized pipe resulted in high thermal losses at the external surface of the pipe. A better diameter of pipe was suggested in the range of 25 mm and 30 mm. It was noticed that at the mass flow rate of 0.01 kg/s or lower, the temperature of PV cell was higher, whereas, as mass flow rate rose to 0.03 kg/s and then to 0.05 kg/s, the temperature of PV cell decreased.

Dubey and Tiwari [23] investigated life cycle cost analysing and carbon credit earning by combined photovoltaic/thermal model. Dubey and Tiwari constructed 2 flat plate collectors that were attached in sequence. Glass-to-glass photovoltaic model with a better area of 0.66 m2 was incorporated into one of the solar collectors. It was claimed that the heating of photovoltaic cell was obtained by absorber plate by converting; water is heated by obtaining heat of absorber plate and transferred in an upward direction. The output of photovoltaic/thermal model was further attached to the input of another solar thermal collector.

Erdil *et al.*, [24] conducted a study on combined photovoltaic/thermal model consisting of two photovoltaic cells, in which every one of them was rated at 55 W possessing dimensions of 13 m × 0.47 m × 0.05 m. Attached to the upper PV cell was a 4 mm thick glass, thus establishing a cavity which cooled water passing from a cold water storage tank which was placed at the upper part of the photovoltaic models. Multi-inputs and outputs manifold models were utilised for a uniformed distribution of water through the cavity. Water passed at the rate of 36 l hourly. It was concluded that partial absorbing and reflecting of solar insulation by the glass cover and the mass of water circulation resulted in 11.5% of electrical output in two enhanced photovoltaic models, as well as achieving the hot water requirement.

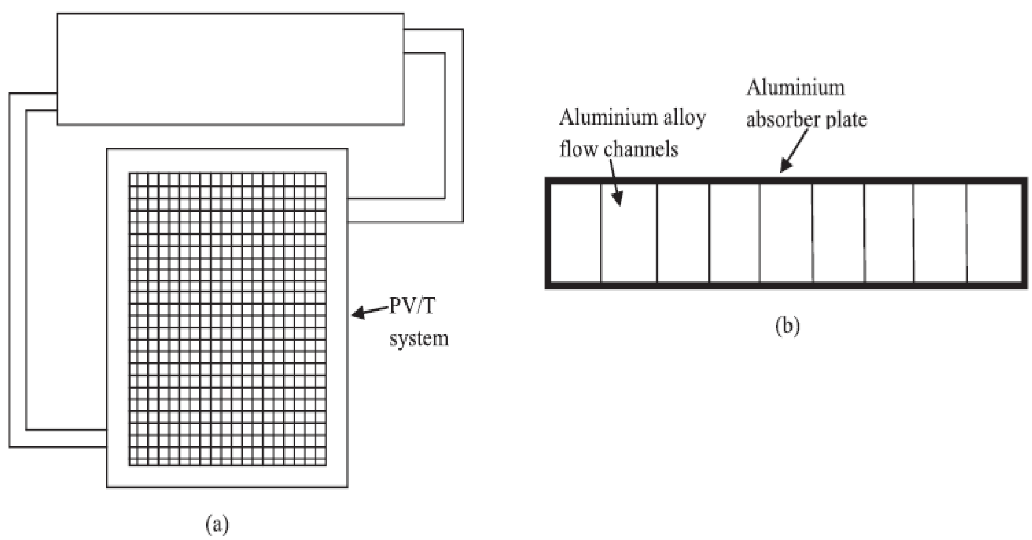

Fig. 5. (a) Front view of PV/T collector, (b) aluminium-alloy flow [37]

Table 1
Summary of previous studies (2012-2017)

Study	Type of PV/T	Type of absorber	Implementation	Findings
[25]	Covered and uncovered PV/T collector	Two aluminium roll-bond absorbers	Simulation and experiment of two different PV/T collectors for comparison	Both PV/T produce similar behavior, however the uncovered PVT is more effective than the covered.
[9]	Uncovered PVT collector	Roll-bond absorber	Simulation model for uncovered PV/T. Experimental testing in outdoor commercial PV/T	The simulation results agreed with the experimental data with less difference due to the assembling faults of the tested PV/T.
[11]	PV/T water collector	Flat plate absorber	Simulation and experimental implementation to analyze the exergy losses	The simulation analysis has agreed to the experimental testing. The study proposed a method to compute the exergy losses.
[14]	Flat plate PV/T collector	Spiral flow absorber	Experimental testing/ Laboratory for three PVT collectors	The investigation results of the study showed that spiral flow absorber produce better efficiency with 68.4 % of PVT efficiency and 13.8% PV efficiency and 54.6% thermal efficiency.
[26]	Combination of the parabolic dish and high efficiency PV/T collector	PV/T absorber	The system was analysed using a mathematical model and subsequently validated by experimental data	Results showed that both electrical and thermal efficiencies are very good in a wide range of operating conditions
[27]	Glass-covered liquid PVT collector	Serpentine pipe and harp pipe solar absorbers	The heat transfer in the PVT collectors were studied by means of computational fluid dynamics (CFD) calculations through the FLUENT 13.0 software.	This study shows that it is possible to optimise PVT productivity by appropriately choosing the collector's thermo-electric configuration. Also harp absorber produce better performance

4. Absorber Design

The collector's conceptual designs, as shown in Figures 6 to 11, consist of seven different design setups. Table 2 presents the components of the absorber design. The absorbers in the shape of round and rectangular hollow tubes were placed precisely below the PV cell with a metallic bond as this would assure a zero gap or no gaps among the tubes and the cell, where heat transferring can be achieved accurately [44]. Chow [45] found that the fin effectiveness and bond quality within the collector, and the sheet below the panel to be the essential factors, which sometimes can be the obstacles in achieving total effectiveness [8].

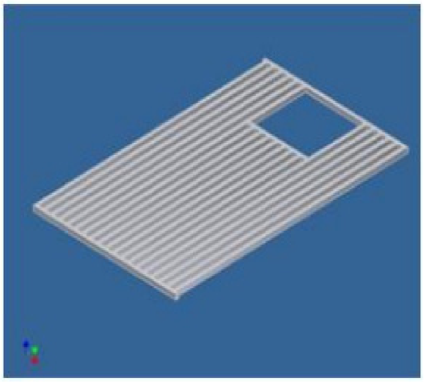

Fig 6. Direct Flow Design

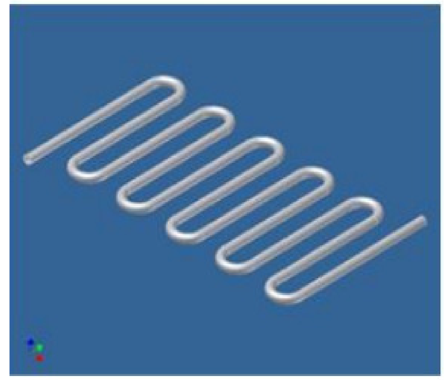

Fig 7. Oscillatory Flow Design

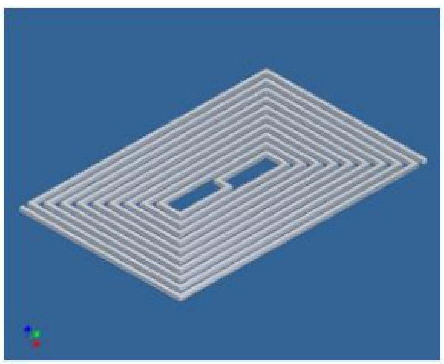

Fig. 8. Spiral flow design

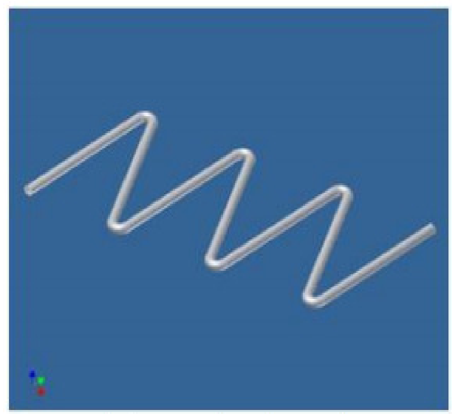

Fig. 3. Serpentine Flow Design

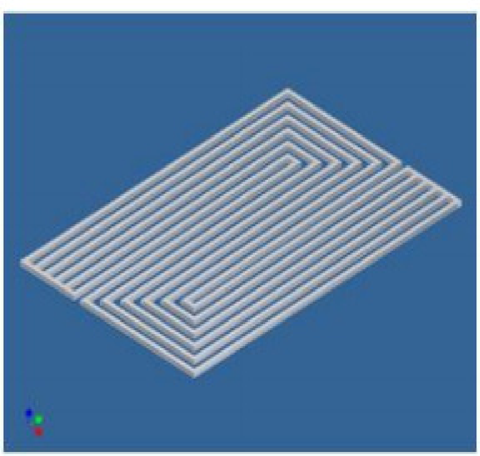

Fig. 10. Web Flow Design

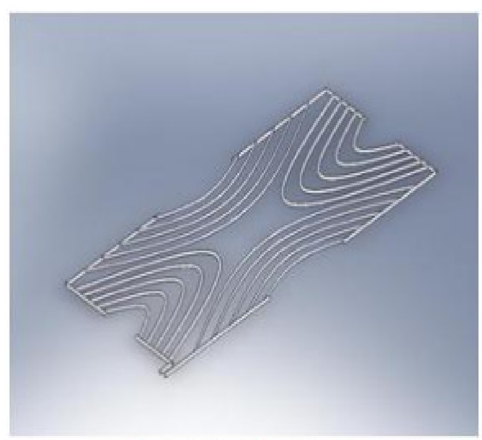

Fig. 11. Parallel-Serpentine Flow Design

Table 2
Parameters of different absorber configurations [8]

Absorber	Description
Direct flow	Absorber components: rectangular hollow tubes of Stainless Steel Absorber module: 19 paths every one sizing of 12.7 mm x 12.7 mm x 1mm x 1000 mm (L) and 640 mm (W) way of combining: Weld input/output number: four.
Oscillatory flow	Absorber components: round hollow tubes of Stainless steel
Serpentine flow, and Web flow	Absorber module: 1 path everyone sizing 12.7 mm x 1 mm x 1000 mm (L) and 640 mm (W) way of combining: Weld input/output number: two.
Spiral flow	Absorber components: rectangular hollow tubes of Stainless Steel Absorber module: 1 path everyone sizing one12.7 mm x 12.7 mm x 1 mm x 700 mm (L) and 640 mm (W) way of combining: Weld input/output number: four.
Parallel Serpentine flow	Absorber components: rectangular hollow tubes of Stainless Steel Absorber module: 6 paths everyone sizing of 12.7 mm x 12.7 mm x 1 mm x 700 mm (L) and 640 mm (W) way of combining: Weld input/output number: two.

5. Conclusion

In conclusion, the aim of this paper is to conduct a critical review of the field of Photovoltaic thermal collector based on water and air. The recent advancement in the field of PVT collector has been analysed by investigating various related studies. Different types of PVT liquid collector were presented and discussed by highlighting their advantages and drawbacks. In addition, different absorber designs were studied in order to analyse their potential performance and production efficiency. The progress in the field of PVT collectors and absorber designs were analysed, in which the drawbacks and limitation of the designs were presented. Different PVT collectors and absorber configurations from previous studies were also examined. The non-uniformity of the heat transfer on the solar PV because of the water flow in the tube absorber also reduce the solar PV efficiency. The design of fluid absorber is very important to increase the heat transfer from the solar PV to water. On top of that, the use of nanofluids to replace the water will have great potential for heat transfer enhancement. However at this moment the price of nanofluids are expensive.

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